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FOR

A SYSTEM AND METHOD FOR IN-AIR ULTRASONIC
ACOUSTICAL DETECTION AND CHARACTERIZATION

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A METHOD AND SYSTEM FOR IN-AIR ULTRASONIC ACOUSTICAL DETECTION AND CHARACTERIZATION

This application claims the benefit under 35 USC § 119 of U.S. Provisional Applications No. 60/425,618 filed November 12, 2002 entitled "System for Acoustical

(U) 10 Characterization" and No. 60/479,168 filed June 17, 2003 entitled "Method and System for In-Air Acoustical Detection and Characterization," both of which which are incorporated herein by reference.

Government Rights

(U) 15 The government has certain rights in this invention pursuant to Contract No. F33615-01-C-6016 awarded by the Department of the Air Force.

BACKGROUND OF THE INVENTION

Field of the Invention

(U) 20 The invention in general relates to detection systems, and more particularly to a system for determining the location of persons and objects via acoustic sensors.

Background

A variety of methods and systems exist for surveillance around buildings and ground assets. One method used to protect the perimeter around a critical facility from

(U) 25 stealthy intruders is to post sentries and trip-wire alarms, or to instrument critical areas with video cameras and have guards monitor the screens. Both of these methods are too human intensive for a large perimeter, and system performance is vulnerable to fatigue by

(U) 5   the guards faced with a tedious task. The modern trend is toward remote sensing of the

entire perimeter to provide automated alerts to which sentries can then be directed, and

otherwise complement the performance of human assets. Further, remote sensing

coupled to automated alerts can lower the cost to defend a perimeter by lowering the

number of human sentries required.

(U) 10   In general, a single sensor type does not provide sufficient detection coverage for

the full variety of expected targets. For example, a quiet stealthy intruder on foot is more

difficult for a passive acoustic sensor to detect than it is for an IR sensor. Several current

intrusion alert systems use video, radar, infra-red, and passive acoustic sensors. All have

varying degrees of problems with excessive numbers of false alarms. Specific

(U) 15   weaknesses associated with these systems, in addition to the high false alarm rates, are

very limited detection ranges (especially for stealthy intruders), and a lack of automatic

threat localization and tracking. Thus these systems could be enhanced with an additional

sensor type that can provide automatic detection coverage for quiet slowly moving

intruders out to about two hundred feet and that can help resolve true from false targets

(U) 20   among the multiple reports.

           Perimeter surveillance systems may use a passive acoustic capability, in the band

of human hearing, to provide covert sensing, target signature recognition, lines of bearing

to contacts and effective information presentation to an operator. Complete dependence

on passive acoustics, however, places some limitations on overall system performance.

(U) 25   Passive sensing alone will not provide adequate detection and localization performance

against a stealthy human intruder, as they move slowly, on foot, and are trained to be

virtually undetectable.

           In other fields, active ultrasonic acoustic systems have been developed which

provide short-range measuring applications such as airbag systems, construction

(U) 5   measurements, proximity warning systems, body imaging, and robotics, such as described

in U.S. Patents 5,577,006 to Kuc and 6,268,803 to Gunderson et al. Most of these

acoustic applications are intended for indoor use and operate at ranges less than 20 feet.

None of the previous applications of the ultrasonic acoustic detections in air were

concerned with extending the operating range of the system for identifying targets to

(U) 10   several hundred feet, nor do they use complex transmit waveforms, array processing or

sophisticated signal processing techniques to improve signal to noise ratio (SNR) and thus

increase the range at which the active echo could be detected. While long range active

sonar array systems are known for underwater applications, similar approaches have not

been introduced into air-acoustic systems because of, among other reasons, the different

(U) 15   characteristics of air versus underwater acoustic environments.

Thus, to date the systems based on air-acoustic detection and characterization

either rely on limited passive systems at human audio frequencies, or are directed at

limited ultrasonic applications like short-range distance measurement or imaging, and

have not attempted to address issues like long-range detection using active air-acoustic

(U) 20   systems at ultrasonic frequencies.

SUMMARY

An embodiment of the invention includes an ultrasonic air-acoustic transmitter

and an air-acoustic sensor. In combination the devices are able to detect objects at a

(U) 25   range of several hundred feet. The air-acoustic transmitter and air-acoustic sensors may

be configured in arrays of transmitters and receivers to increase performance.

Additionally, the invention provides for a unified system of multiple transmitters and

sensors working together to detect objects more accurately and over a larger area.

(U) 5   Further, the invention provides computer analysis through signal- and post-processing of the signal returns (i.e. reflected waves or signals that are detected at the acoustic sensors).

     One embodiment of the invention includes a new approach to improved surveillance capabilities for facilities and ground assets. One means of reducing false alarms in such systems is the simultaneous use of multiple air-acoustic sensors that

(U) 10   overlap in coverage but depend upon different target or environmental characteristics for detection. Combining or fusing the scenes developed by the individual sensors can then reduce false alarms. This embodiment introduces ultrasonic active acoustic in-air sonar to enhance the performance of multi-sensor remote surveillance systems. This ultrasonic active in-air sonar can be integrated with other surveillance sensors such as passive

(U) 15   acoustic, IR and video sensors to provide more robust, capable surveillance coverage. An active ultrasonic detection system, operating above the range of human hearing, can detect stationary or moving stealthy intruders out to a range of two hundred feet or more, without alerting the intruder, and provide an automatic localization and tracking capability. It can also reduce false alarms prevalent in passive systems, and while passive

(U) 20   sensors provide only bearing to a target, the active acoustic system measures target direction, range and range-rate. It would therefore allow for the detection of extremely quiet human intruders that are either moving or stationary and would do so without directly alerting them. It would also in no way affect the lower frequency passive listening portion of the system and the use of it at any time by the command post to have

(U) 25   a virtual presence in the field.

4

DRAWINGS

The invention may be more readily appreciated from the following detailed description, when read in conjunction with the accompanying drawings, in which:

Figure 1 is a block diagram of an active air-acoustic system including a transducer array and a signal processing platform.

(U) 10 Figure 2 illustrates the absorption coefficient based on the humidity and temperature used by an embodiment of the present invention.

Figure 3 is a block diagram of the post-processing of the received signals of an embodiment of the present invention.

Figure 4 illustrates an exemplary deployment used by an embodiment of the

(U) 15 present invention.

Figure 5 illustrates the theoretical coverage of a plurality of sensors of the present invention.

Figure 6 illustrates the theoretical sensor coverage of one implementation of the present invention.

(U) 20 Figure 7 illustrates a graphical display of a moving human target as viewed by the present invention.

Figure 8 illustrates a graphical display of two stationary human targets as viewed by the present invention.

Figure 9 illustrates a schematic for one embodiment of a portion of the transmitter

(U) 25 of the present invention.

Figure 10 illustrates a schematic for one embodiment of the transmitter array of the present invention.

Figure 11 illustrates a schematic for one embodiment of the receive array of the present invention.

Figure 12 is a diagram of a transmitter and a receiver oriented perpendicularly to one another.

Figure 13 illustrates a graphical comparison of measured vs. predicted SNR for
(U) 10 one implementation of a system according to Figure 1.

DETAILED DESCRIPTION

The present invention provides a system and method to extend perimeter detection through the use of an in-air active acoustic system. According to one embodiment of the
(U) 15 invention, this is accomplished through the novel use of active acoustic sensors that operate at ultrasonic frequencies for long-range in-air detection. Ultrasonic frequencies are generally frequencies above those audible to humans, typically above 20kHz. Transducer arrays are used for beamforming and signal processing techniques are used for detection and target characterization. These signal processing techniques are more
(U) 20 advanced than range determination. As discussed below in more detail, the features and combination of features herein have not been developed in the past for reasons including a lack of information regarding in-air environmental ultrasonic characteristics, ultrasonic noise sources, ultrasonic target reflectivity or ultrasonic array development.

An embodiment of the invention may be better understood by reference to Figure
(U) 25 1. The performance of an active system depends on a variety of factors. The source frequency and power level need to be selected based on the environment, the efficiency of the source, and the target reflectivity. Characterization of a target generally involves measuring or modeling the amount of energy that is reflected from stealthy intruders. The

(U) 5   basic signal return in active air-acoustics (sonar) is a plane wave reflection that correlates with a delayed and possibly frequency shifted version of the transmitted signal. The plane wave property is the result of the target being relatively concentrated in the environment, and can be modeled as a point reflector in the far field of the receiver. This allows spatial filtering to be performed that can help reject energy from directions other than the

(U) 10   direction of interest for the target. This spatial processing may utilize a conventional beamformer that produces main lobes in the desired steering directions and low sidelobes to reject energy from other directions. Sometimes there is a need for more sophisticated beamformers that adapt to the environment to reject strong plane wave energy from other directions. These are referred to as adaptive beamformers.

(U) 15   There are a variety of noise sources that can mask reflections from an intruder. They should all typically be considered, and some of them are related to the transmitted signal itself. There is of course background ambient noise that exists everywhere. This can vary in level dramatically depending upon just how quiet the locale is at the time. For example, a quiet forest or rural area would present a much lower noise floor to the system

(U) 20   than an urban area or an airport. One can also expect there to be backscattering of the active transmission. This source of noise is called reverberation and is primarily from large diffuse reflecting regions such as boundaries like the ground or dense foliage. Another form of backscatter/clutter, is more specular or distinct, and comes from smaller reflectors that are very localized and almost point-like. Clutter returns behave like targets

(U) 25   in many ways since they are plane waves that correlate with the transmitted waveform. They can, for example, be echoes from trees or small structures or equipment. In the perimeter protection mission, the sensors and most clutter are in general stationary, while the target moves into and around in the field of view. It is therefore possible to characterize much of the clutter during known non-intruder conditions. One embodiment

(U) 5   employs a Clutter Map, which is an estimate of the background reflections during a non-target period, used to normalize the background.

These returns can then be ignored, and the system can detect changes to the normal background. Such changes may occur as animals wander into the area being protected. The signal processing to detect human intruders will typically initially declare

(U) 10   these to be threat targets. They will have to be eliminated from consideration by classifying them based on other properties. These properties can be extracted by over-resolving the target structure to detect highlights. The highlights reflected from a human intruder will have a different shape or extent than those of an animal intruder. They may also move differently, and exhibit some natural radiated sounds that could help

(U) 15   distinguish them from threats. They should typically be dealt with in the post-detection processing portion of the system. The post-processor characterizes the threats, vehicles, and other reflectors likely to be encountered with clues about their size and expected motion. A feature classifier and motion tracker are then used to decide whether the returns are threat related.

(U) 20   Another source of noise expected in an active system for remote monitoring is plane wave interference. This is strong acoustic radiated energy in the band of the active sonar receiver from other directions than the direction that the beam is steered to for threat detection. It is not correlated with the transmitted waveform, but it can be strong enough to come through the matched filters that are matched to the transmitted waveform

(U) 25   and mask the target return. It is planar, but from a different direction than the transmitted signal. Because of this directional property, it may be rejected spatially, using conventional or adaptive beamforming. Airplanes taking off or landing within the perimeter being monitored are likely examples of this type of interference. Those

(U) 5   directions will have to have large amounts of rejection, perhaps even nulls, in the spatial

response.

Table 1 summarizes some of the design considerations for the application of

active sonar to the remote detection problem.

Table 1. Considerations for Application of Active Sonar to Remote Auditory Detection

PROPERTY TO BE CHARACTERIZED	SONAR TERMINOLOGY	LIKELY CAUSE	TYPICAL PROCESSING
Reflectivity of intruders and non-threats	Target strength	Size, surface hardness, aspect angle	Use matched filters looking for correlation with the transmitted signal
Diffuse ambient noise	Background noise level	General background in the area	Use an array of sensors and form beams with low sidelobe responses in directions that are not of interest
Diffuse non-moving backscatter from the surrounding terrain	Reverberation	Boundaries such as the ground or foliage	Use Doppler processing so that if the targets move they are away from the zero Doppler reverberation
Concentrated threat-like backscatter	Clutter	Trees, out-buildings, animal intruders, non-threat traffic	Look for clues in shape or motion or other sounds

Directional ambient noise	Plane wave interference	Strong concentrated radiated noise, such as airplanes, road traffic, or machinery associated with the base infrastructure such as electric generators, etc.	Spatial nulling using adaptive cancellation or adaptive beamforming

(U) 5

Turning to Figure **1**, an in-air active acoustic system according to one embodiment of the invention is illustrated. An array of radiators (transducers) and microphones is used for transmitting and receiving sound. The array provides signal gain, directivity, and rejection of unwanted noise. In some cases an array with fixed spatial response does not

(U) 10   reject enough of the unwanted interference, and adaptive beamforming may be advantageously used to provide further nulling of the noise. The receive system includes signal conditioning, dynamic range control, digital conversion, digital receive beamforming, and filtering of the resulting multiple beams.

The active detector matches filters to delayed and frequency shifted versions, of

(U) 15   the transmitted waveform. A typical active sonar display will be a range-Doppler map including of the matched filter outputs for each of the resolution cells corresponding to different range and frequency shifts.

For active sonar, there are many returns that are not due to random noise, but instead are due to reflections back from the environment. When a distributed region

(U) 20   around the target scatters back to the receiver, this backscatter is referred to as reverberation. In the ocean this can occur in the water volume, or at the surface or bottom boundaries. The reverberation comes back from stationary scatterers and is therefore at zero or very low Doppler shifts, depending on the motion of the receiver, its beam

(U) 5   sidelobes and waveform ambiguity functions. If the target is moving relative to the receiver, then its Doppler shift will move it out of the reverberation on the range-Doppler map. The detection of stationary or slow moving targets can be limited by reverberation rather than background noise, because they fall within the ridge of reverberation response in the low Doppler region of the range-Doppler map. Distinct objects can also reflect

(U) 10   back energy and appear as targets. These false targets are referred to as clutter, and post processing is used to distinguish clutter from true targets. This processing involves examining the structure of the active sonar return for distinct features or clues that are representative of targets or non-targets.

A useful measure of the performance of a sonar is the signal-to-noise ratio

(U) 15   available at the output of the array for subsequent signal processing for detection or estimation. The performance is characterized by active sonar equations, which predicts the available signal-to-noise ratio that the system provides for detection of the target and estimation of its location and identifying characteristics. Table 2 illustrates an active sonar equation stated in terms of decibels.

(U) 20

Table 2. Active Sonar Equation

ACTIVE SONAR EQUATION: SNRAV= SL - 2TL + TS - (NL – DI) – RL
where
SNRAV = signal-to-noise ratio available to the receiver
SL = source level of sound source in decibels relative to 1 microPascal (μPa), the unit of sound intensity
TL = transmission (propagation) loss in dB, one way from source to target or target to receiver
TS = target strength in dB of active sonar target, related to its sound reflectivity
NL = noise level at receiver in dB re 1µPA (assumed to be omnidirectional)
DI = directivity index of receive array in dB, amount by which the array rejects the omnidirectional noise
RL = reverberation level at the receiver

Applying the equation of Table 2, it can be seen that the available signal-to-noise ratio for active sonar is the transmitted signal power decreased by the two-way propagation loss, modified by the target reflectivity, compared to the noise power at the

output of the directional receiver.

The field of underwater sonar has developed performance prediction techniques based upon the sonar equation, and the terms in the sonar equation have many parametric dependencies and environmental sensitivities. A tremendous amount of effort has been spent over the years to understand this behavior in the ocean for systems that detect,

(U) 5   targets such as submarines and mines. For the acoustic detection of human intruders in

air, the amount of characterization data is very limited, and has been independently

gathered via experimentation in the process of developing the embodiment of the present

invention. **Table 3** shows how some of the sonar equation terms may vary as a function

of system or environmental parameters.

(U) 10   Table 3. Parametric Dependencies of Terms in the Sonar Equations

Term	Characterization
SL	active: transducer efficiency, power, operating frequency;
	passive: target type, speed, location
TL	frequency, range, sound refraction, weather, season, attenuation
TS	frequency, target size, aspect orientation, composite structure
NL	frequency, location, BW, density of other traffic, weather, biologics
DI	frequency, array geometry, correlation properties of the noise
RL	source level, scattering strength, pulse length, beam widths on both transmit and receive

Figure 2 illustrates the absorption coefficient versus temperature and humidity

for waveforms of 21,500 Hz. From this figure one can see that the range of

absorption coefficient values from 0.12 to 0.22 covers the large majority of typical

(U) 15   temperature/humidity values. Very little can be done to mitigate the impact of

absorption. One may lower the frequency but eventually the frequency enters the

audible frequencies and the covert nature of the system is lost. It is important to

understand the impact of the absorption to realize that the system performance will

13

(U) 5　change drastically from one month to another and, to a lesser extent, across the course

of a day as the temperature and humidity fluctuate. The data from this figure is used

by the system in situ to adjust the parameters of the present invention to take into

account the temperature and humidity of the area under surveillance. An embodiment

of the present invention provides for sensors to determine the humidity and

(U) 10　temperature of the area under surveillance and a mechanism to provide these values to

a processing unit.

The use of an in-air active sonar for area surveillance includes characterization of

the sources, environments, and targets. In the active sonar case at ultrasonic frequencies,

most of the parameters needed for evaluating the performance via the active sonar

(U) 15　equation have not been investigated. In one embodiment of the invention, a system for

measuring the parameters of the environment and the targets, and to characterize

detection performance, includes:

1. multiple transmit elements that are coherently combined to form a transmit

beam;

(U) 20　　2. variable operating ultrasonic frequencies to measure sensitivity across the

band;

3. single frequency and frequency swept transmit waveforms to detect stationary

(low Doppler) and moving (high Doppler) targets in background

reverberation;

(U) 25　　4. multiple receive elements coherently combined to form receive beams with

array gain, directivity, and interference rejection;

5. active sonar signal processing, performing the waveform matched filtering to

form a range-Doppler map of the active sonar returns;

14

6. active sonar data processing (employing clutter mapping to normalize non-uniform background responses, followed by a sequential detector to accumulate target returns from multiple pings), and active decluttering (employing feature estimation on clusters of returns to classify real from false targets);

7. a range-Doppler display of the active sonar response in different beams (directions) for an initial operator interface; and

8. extension to automatic detection and alerting for input to a future data fusion system incorporating similar results from other sensors.

Additional design elements for embodiments of the invention may include any

combination of the following:

1. The absorption of sound in air increases dramatically as the operating frequency is increased. Thus for the longest detection range the ultrasonic system should transmit at just above the audio band, i.e. in the 20 to 25 KHz region. If higher resolution is needed and shorter ranges can suit the situation,

then the frequency can be increased accordingly.

2. There are inexpensive commercial ultrasonic transducers on the market. These element outputs can be used to make the transmit array, and the gain and phase stability of the elements supports the formation of a transmit beam with increased source level over that of a single sensor.

3. The existing inexpensive commercial ultrasonic transducers on the market cannot be used for receive directional beamforming because the elements typically are physically too large and do not have sufficient gain and phase stability to form directional beams. Instead, one implementation uses low cost

(U) 5   acoustic microphones that normally are operated in the audio band. The

sensors within these microphones have significant response in the ultrasonic

band, but this is usually not used since it is beyond the range of human

hearing. The filters and pre-amplifiers can be changed to process the outputs

of these sensors only in the ultrasonic band of interest, resulting in a very low

(U) 10   cost receive array with gain and phase stability across the elements that

supports the formation of directional beams.

Turning back to Figure 1, each of the components and modules of an embodiment

of the invention are described below. The components and modules may include

(U) 15   hardware (including electronic and/or computer circuitry), firmware and/or software

(collectively referred to herein as "logic"). A component or module can be implemented

to capture any of the logic described herein. The transmitter includes waveform generator

module 101, transmit electronics module 102, and transmit array module 103. The

receiver includes a receive array module 104, front end electronics module (that includes

(U) 20   signal conditioning and dynamic range control) 105, and an analog to digital converter

module 106. The subsequent signal processing includes clutter mapping module 107,

single ping detection module 108, clustering module 109, a low Doppler notch filter

module 110, feature extraction module 111, sequential detection module 112 and

generation of displays module 113.

(U) 25   One embodiment of the transmitter is described in Figures 9 and 10. The

waveform generator 901 stores versions of narrowband sinusoidal (or continuous wave

(CW)) signals, or broadband swept hyperbolic frequency modulated (HFM) signals and

digitally generates the desired waveforms (selected from a set of shaped CW or HFM

pulses of various pulse lengths) at a preselected sample frequency. The waveform

(U) 5   generator is a logic module. The digital waveform data is transformed to an analog signal

with a digital to analog converter **902**. The resulting analog signal is filtered to eliminate

signal content outside the frequency band of interest with a Band-Pass Filter. The filtered

transmit signal is then amplified with amplifier **903**, and output to the Transmit Array

described in Figure **10**. The Transmit Array may be a single transducer **1001**, an array of

(U) 10   transducers, or multiple arrays. In all configurations, the elements of the transmit array

are capable of coupling the high power waveform signal into high levels of ultrasonic

acoustic energy in the air. The array of transducers provides an increase in total

transmitted power as well as spatial directivity of the transmission that allows the transmit

energy to be focused substantially in a single desired direction and minimized in other

(U) 15   directions. The waveform generator may produce several waveforms that are

concatenated wave into a wavetrain. One example of a such a concatenated waveform

would be the use of a CW waveform for rapidly moving targets, a long-duration HFM

waveform for distant slow moving or stationary targets and a short-duration HFM

waveform for close in or slow moving targets, i.e. first generating a CW waveform

(U) 20   followed immediately by a short duration HFM immediately followed by a long duration

HFM. Immediately can mean within a very short time duration, optimally less than a

millisecond.

An embodiment of the receiver is described in Figure **11**. The Receive Array **104**

for receiving ultrasonic-signals may be a single receive sensor, an array of sensors, or

(U) 25   multiple arrays. The array electronics provide an analog filter to reject out of band signals

and provide gain to scale the signals to be within the dynamic range of the analog to

digital converter. The array of transducers provides spatial filtering to reject waveforms

from undesired directions and to provide signal gain. The output signals from the receive

17

(U) 5   array are amplified and filtered with low noise microphone preamplifiers **105, 1101** and

transformed to a digital form with an analog to digital converter **106**.

An embodiment of the signal processing procedure is described below. The

signal processing includes single ping detection module **108** and creation of a clutter

map by module **107**. The first step in the processing sequence after the received data

(U) 10   has been digitized and passband filtered is single ping detection in module **108**. This

refers to the processing performed to produce the individual resolution elements

supported by the waveforms and determining the presence or absence of a signal in

those elements. This processing includes matched filtering with overlap to reduce

scalloping between range bins. An overlap of 75% is used in an embodiment of the

(U) 15   invention. In order to map the matched filter output bins to signal-to-noise, a

representation of the noise background is developed by creating a clutter map over

multiple pings by averaging the range maps (HFM waveforms) and range-Doppler

maps (CW waveforms) over a large number of pings. This clutter map is calculated

periodically or whenever something in the environment changes substantially.

(U) 20   Dividing the clutter map into the single ping range or range-doppler maps produces

resolution cells that are proportional to signal-to-noise ratio. The resolution elements

are compared to a threshold, with those exceeding the threshold assumed to contain a

useful signal. It should be noted that because of the high range resolution of the HFM

waveform and the high doppler resolution of the CW, the system may over-resolve a

(U) 25   contact, producing threshold crossings in multiple resolution elements. ("Over-

resolve" may in general refer to receiving more than the minimum data necessary to

resolve a feature to a predetermined resolution.) The post-processing includes

processing to group these multiple threshold crossings into individual detections (i.e.

correlate or modify the signals to refer to a single target or feature) and reject false

18

(U) 5   alarms based on their spatial and temporal characteristics (for instance, rejecting as

false alarms signals that are not closely associated in time or position).

The post processing includes clustering module **109**, a low Doppler notch **110**,

feature extract/declutter module **111**, a sequential detector module **112**, and display

processing module **113**. The clustering function groups multiple threshold crossings

(U) 10   that are in close enough proximity to one another so that they represent the over-

resolved echo return from a single object. The low Doppler notch is a filter that

rejects low Doppler CW detections, since actual targets exhibiting Doppler as low as

this are moving slowly and are more effectively detected using the HFM waveform.

The feature extract/declutter module or logic **111** detects a variety of predetermined

(U) 15   cluster characteristics that can be used to discriminate which echo returns are from

actual targets of interest. Such cluster characteristics can include shape, energy

contents and/or other physical characteristics of reflected acoustic waves that

correspond to features of a target. The output from module **111** includes in one

embodiment digital information or data packets encoded to represent such cluster

(U) 20   characteristics which are transmitted to the sequential detector **112.**

The sequential detector module **112** performs a method which integrates

returns over multiple pings in order to reduce or eliminate returns due to background

noise and to efficiently detect target returns. One embodiment of a suitable sequential

detector sequential detector module **112** is further shown in Figure **3** and described

(U) 25   below. The integration to reduce background noise can be carried out by summing,

averaging, normalizing or otherwise processing the received signals to increase the

target-signal-to-background ratio.

In post-processing, outputs from the preceding stages (received via sequential

detector module **112**) are rendered by display logic (which may be integrated into the

19

(U) 5   engineering displays module **113**) and are either thresholded for automatic detection

alerts, or displayed for visual observation by an operator. Information can be

displayed in a variety of ways depending on the actual application and the needs of

the operator.

Figure **3** describes the post processing for this system, the function of which is to

(U) 10   take the detections from the signal processor and preserve those threshold crossing that

were due to real targets and remove those from false targets. Proper setting of all the

parameters present in this portion of the processing includes evaluation and tradeoffs of

characteristics such as detection performance, false alarm rates and association of target

returns across multiple pings. Evaluation of these characteristics for real data was used to

(U) 15   select values for post processing parameters such as: cluster gap sizes, cluster size

limitations, detection thresholds, sequential detector association gates, sequential detector

likelihood parameters, sequential detector missed opportunity penalty and sequential

detector thresholds.

For the purposes of this discussion the modules in Figure **3** are referred to as

(U) 20   follows: small cluster filter module **301**, input threshold module **302**, LLR calculation

module **303**, association gates module **304**, start threshold module **305**, detection pre-

tracks module **306**, predict position module **307**, CLLR accumulation module **309**,

threshold comparison module **310**.

The initial filter module **301** removes clusters that include of one or two detected

(U) 25   cells that are smaller than targets. The next step in the processing is an amplitude

threshold module **302**. If this threshold is too low then many false alarms will pass

through the automatic detection system. If it is too high then targets may be eliminated.

The goal is to lower this threshold as much as possible in order to increase the probability

of detecting a target, to within the limits of the subsequent processing at removing non-

20

(U) 5   targets or clutter. The subsequent processing processes multiple pings to reach an

automatic detection decision. In this case a sequential detector is used, but other

combining techniques can be used as well. The sequential detector includes of modules

303 through **309**. The first step is to determine the log likelihood ratio (LLR) of each

cluster. The LLR is the logarithm of the ratio of two likelihood functions: one is the

(U) 10   probability that the received echo occurred assuming the presence of an actual target,

while the other is the probability the received echo occurred assuming no target was

present. A common detection strategy is to compare this LLR to a threshold after a fixed

number of pings in order to decide whether to declare a detection. Alternatively, in the

sequential detection approach used here, a cumulative LLR (CLLR) **308** is updated after

(U) 15   each ping and the CLLR is compared to two different thresholds **309**. If the CLLR is

greater than the report threshold, a detection is reported; if the CLLR is lower than the

drop threshold it is considered a non-detection event and removed from further

consideration. If the CLLR is between the two thresholds, no decision is made. For a

desired set of probability of detection (Pd) and probability of false alarm (Pfa) values, a

(U) 20   sequential detector produces fewer pings (on average) to call a detection then a detection

strategy based on a fixed number of pings. The CLLR is calculated for a sequence of

clusters associated across multiple pings **304**. After each ping, new clusters are compared

to existing cluster sequences to determine whether they should be associated with an

existing track or pre-track. Parameter adjustments can be made to the algorithm used to

(U) 25   predict future positions **307** as well as the size of the association gates used to identify

which new clusters are "close" enough to associate with an existing pre-track. Clusters

that do not associate with an existing pre-track are used to initiate new pre-tracks if they

are above a start threshold **305**. The CLLR of pre-tracks **306** that are not updated with a

new cluster are decremented by a "miss" penalty so that after some number of pings

21

(U) 5   without an update the pre-track will be dropped. Parameters such as the various

thresholds, the miss penalty and the association gates can be carefully chosen based on

expected target motion as well as characteristics of the waveforms. Parallel strategies can

be implemented that simultaneously search for both slow moving and rapidly moving

targets. The slow moving targets are those detected with the short or long broadband

(U) 10   (HFM) waveforms, while the rapidly moving targets are those detected with the

narrowband (CW) waveform.

Figure **4** illustrates an exemplary deployment used by an embodiment of the

present invention. In this embodiment there is one transmitter array **401** to transmit

waveforms over a broad enough sector to encompass all of the receive beam directions.

(U) 15   The transmitter receives waveforms from the transmit/receive box **405**. The transmitter

transmits an ultrasonic wave **402** to provide a main lobe that is (in this example)

approximately 50 degrees wide. In this embodiment, multiple receive arrays **403** may be

provided, each of which may be identical or similar to receive array **1101** shown in

Figure **11** or receive array **1201** shown in Figure 12. See Figure 4A for one possible

(U) 20   configuration using four receive arrays **403**. The receive arrays **403** each have a receive

capability of approximately 17 degrees in this embodiment (or some other predefined

angle). Therefore, each receiver has an overlapping responsibility with the receiver next

to it while covering the 50 degrees of transmitted ultrasonic waves. These receivers may

be stacked one on top of the other at slightly different angles in order to create this

(U) 25   feature. The receivers all provide their reception data to the transmit/receive box **405** so

that the reception data may be passed on to a processor for further processing of the return

signals.

22

(U) 5   This configuration reduces noise from unwanted directions (i.e. directions other than the selected 50 degrees for the transmitter for this example by making the side lobes as small as possible).

Figure 5 illustrates the coverage of a plurality of sensor arrays. A sensor array with a given sensor spacing and a field of view of angle α may be used with a standoff

(U) 10   range of y and a depth of coverage of d. The depth of coverage d is the effective detection area of the sensors. The lower limit of d is the minimum distance of an entire region by multiple waveforms is assured. Integration logic is used to receive the received waveforms and allow several receivers outputs to be processed by one processing module. It is able to combine returns from single targets to multiple arrays into a single

(U) 15   target reported to the graphical interface logic. The stand-off range is the range where the return signal is below a predetermined threshold.

Figure 6 demonstrates the theoretical sensor coverage of one implementation of the present invention with waveforms of 100 msec in duration. The waveform with a 100 msec duration produces a blind range (the time during which echoes would be masked by

(U) 20   the transmission itself) of 55 feet, so if coverage of this area is to be provided, a short pulse can be interleaved with the longer pulses. This waveform can be sufficiently long to provide detection out to at least 55-60 feet. A 25 msec HFM waveform, which has demonstrated detection to beyond 80 feet, was selected as the waveform to provide close-in coverage. It provides some overlap with the 100 msec waveform and has a blind range

(U) 25   of about 14 feet. This interleaving of pulses of various lengths allows for the system to advantageously detect targets over a greater area than would be possible with pulses of one waveform.

Figure 7 illustrates a graphical display of a moving human target as viewed by the present invention. The location and level of the various shadings represent the strength of

23

(U) 5   the echo return and the amount of movement of the object as determined by the signal

processor. In this example, the target is moving at 20 feet per second.

Figure **8** illustrates a graphical display of two stationary human targets as viewed

by the present invention. In this example two stationary targets are located at

approximate distance of 120 and 140 feet. These targets are specified by the high return

(U) 10   level at those distances.

Figure **9** demonstrates the schematic of an embodiment of a portion of a

transmitter module of the present invention. The schematic shows a micro-controller **901**

used to generate digital waveform data for the desired waveform at the sample frequency.

The digital waveform data from the micro-controller is transformed to an analog signal

(U) 15   with a digital to analog converter **902**. The resulting analog signal is filtered to eliminate

signal content outside the frequency band of interest with an eighth order Band-Pass

Filter **903**. The filtered transmit signal is then amplified with a solid state amplifier.

Figure **10** demonstrates the schematic of an embodiment of a transmit array. The

schematic shows a five element transmit array, with each element of the transmit array

(U) 20   receiving the full amplitude of the transmit signal from the transmitter module described

in Figure **9**. The schematic shows the matching networks selected to tailor the response

of the individual elements for the desired bandwidth of operation.

Figure **11** demonstrates the schematic of an embodiment of a receive array. The

schematic shows four separate 10-element receive arrays that provide four receive beams

(U) 25   at desired angles. Each receive array includes a line array of microphone elements **1102**.

This schematic shows the use of electret-condenser audio band microphones **MIC$_n$** used

at ultrasonic frequencies. The outputs of each microphone element in the line array are

summed to form a single channel output or beam. The four beam outputs from the array

(U) 5　　are output for subsequent amplification, analog to digital conversion, and signal

processing.

　　　　　Figure **12** is a diagram of a transmitter and a receiver oriented perpendicularly to

one another to reduce the reverberation or backscatter in the overall response, which is

the intersection of the transmit and receive beams. Receiver array **1201** includes

(U) 10　　microphone elements **1202** oriented in one longitude (in this case horizontal).

Transmitter array **1203** includes transmitters **1204** oriented in a second longitude (in this

case vertical). As can be seen the receiver array **1201** and the transmitter array **1203** are

oriented perpendicular to one another, which is known as Mills Cross configuration.

Generally, the arrays **1201** and **1203** include two or more transmitter and microphone

(U) 15　　elements respectively.

　　　　　Figure **13** presents the results of actual field measurements collected using a

system including arrays similar to those as described above. The plot shows signal to

noise ratio (SNR) at the output of the sensor system versus range to a human target. The

black and red curves show theoretical estimates of SNR for the prototype system

(U) 20　　presently available using (respectively) a 10 millisecond and a 40 millisecond transmit

pulse; the performance curves assume nominal environmental conditions. Measured data

points from two different test days show that the prototype equipment is achieving the

basic level of performance theoretically predicted. The green (diamond shape) curve

shows the estimated performance for a system using a higher power transmission, a larger

(U) 25　　receive array, longer transmit pulses and processing that includes integration across

multiple pings.

　　　　　Some of the benefits that may be realized from the inventive features discussed

above include:

1. Use of active ultrasonic sensors for long-range detection, localization and classification;

2. Utilization of high-Q ultrasonic sensor elements to create a multi-element transmit array;

3. Utilization of low-Q audio microphones to create a multi-element, receive

   array operating in the lower end of the ultrasonic frequency band (these components support electronic steering of the receive beams);

4. Characterization of ultrasonic noise backgrounds, target reflectivity, and environmental scattering levels;

5. A detection capability out to operationally meaningful ranges for detection of

   a stealthy intruder around a high valued facility (i.e. on the order of several hundred feet);

6. A reliable detection mechanism that:

   i. does not rely on energy radiated by the intruder

   ii. is difficult to spoof

   iii. will not alert stealthy intruders;

7. A detection mechanism that operates via different physical principles than other commonly used in-air surveillance sensors, providing complementary performance in a multiple sensor system;

8. Introduction of an active, covert sensor into in-air, perimeter surveillance

   systems that provides:

   i. A localization capability that provides range, cross range, and rate range information on targets

ii. A high resolution capability due to high frequency operation that can provide target features for classification purposes;

9. Operation at high acoustic frequencies for which wavelengths (and the resulting physical array aperture sizes) are small, thus providing a compact sensor system with very low power consumption;

10. A low cost approach to wide area intrusion detection;

11. A system that can exploit a variety of sonar detection processing techniques, including algorithms designed for use in underwater sonar applications, including:

i. Beamforming on transmit and receive. Sensors are formed into

antenna arrays for both increased source level and directivity on transmit, and to support multiple beam processing on receive. The array elements can be processed with a conventional beamformer to provide fixed beams, or with an adaptive beamformer to provide additional interference

rejection.

ii. Multiple sidelobe canceling can be performed with auxiliary array elements to reject plane wave interference

iii. The use of complex active sonar wavetrains and waveforms to simultaneously test for high and low Doppler targets

iv. The use of clutter mapping and spatial-temporal normalization techniques to smooth non-uniform responses to background noise

v. Accommodation of monostatic or bistatic operation, i.e., not requiring that the transmitters and receivers be collocated

12. Can be easily be tailored to different perimeter geometries and a layered defense approach; and

13. Can operate in-air over land or water.